SOZZETTI Alessandro
INAF – Osservatorio Astronomico
di Torino
Strada Osservatorio 20
10025 Pino Torinese
Italy

STAVINSCHI Magda
Astronomical Institute
Romanian Academy
Cutitul de Argint 5
RO 040557 Bucharest
Romania

TANG Zheng Hong
Shanghai Astronomical
Observatory CAS
80 Nandan Rd
Shanghai 200030
China PR

VAN ALTENA William F.
Astronomy Department
Yale University
PO Box 208121
New Haven CT 06520-8101
United States

WALLACE Patrick T.
Space Science & Technology Department
STFC
Rutherford Appleton Laboratory
Harwell Oxford
Didcot OX11 0QX
United Kingdom

ZACHARIAS Norbert
Astronomy Department
US Naval Observatory
3450 Mass. Ave. NW
Washington DC 20392
United States

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3   Ground-based opportunities for astrometry

NORBERT ZACHARIAS

Introduction

Chapter 1 surveys the opportunities and challenges for astrometry in the twenty-first century (van Altena 2008) while Chapter 2 discusses space satellites primarily designed for astrometry. We now review the situation for ground-based astrometry, since it is often mistakenly stated that there is no longer any need to pursue ground-based research once satellites are operating. It is certainly true that the levels of precision and accuracy projected for Gaia and others are far beyond what can be achieved from the ground. However, there are also consequences of the fairly small aperture size and short flight durations that impose constraints on the limiting magnitudes and our ability to study long-term perturbations. In this chapter we will explore those areas of research using astrometric techniques that will be able to make important contributions to our understanding of the Universe in the coming years, even with high-accuracy satellites such as Gaia operating.

3.1   Radio astrometry

It is likely that radio astrometry observations (see Chapter 12 for a detailed discussion of radio astrometry and interferometry) will continue to be made primarily from the ground due to the difficulty and cost of launching large objects into space. Since the diffraction limit of a telescope is inversely proportional to the wavelength and radio wavelengths are about 10^3 to 10^5 times longer than those of visible light, no high-resolution imaging or high-precision angular measures can be performed with a single radio telescope. The technique of interferometry and in particular very long baseline interferometry (VLBI) overcomes this problem (Thompson *et al.* 2001). VLBI connects radio telescopes across the globe and results in angular measures far more precise (order 0.1 mas) than obtained by traditional ground-based optical telescopes.

Following centuries of optically defined fundamental systems (Walter and Sovers 2000), a fundamental change was made for the International Celestial Reference Frame (ICRF) with its latest incarnation, the ICRF2 (see Chapters 7 and 8 for a detailed discussion of celestial coordinates and the ICRF). The modern reference system is now defined by VLBI

observations of about 700 compact extragalactic sources (ICRF2 resolution, IAU General Assembly, 2009, Fey *et al.* 2009). VLBI observations are very accurate but reductions are complex since they have to solve for Earth orientation, plate tectonics, geophysical and other parameters simultaneously with the astrometric parameters (source positions). Since the reference sources are extragalactic, a mean zero motion and rotation of the ensemble of extragalactic sources is assumed. However, most of these radio sources are galaxies and the structure of their images has become an issue so VLBI observations now push to higher frequencies where this structure becomes less of a problem (Charlot *et al.* 2010).

A continuing problem with reference systems is that in order to obtain the highest accuracy, it is necessary to limit the reference objects included in the system to those objects with the highest-accuracy positions. As a consequence, there are few sources to which new observations may be referred. The next step is to incorporate more sources into the radio reference frame. Currently (www.vlba.nrao.edu/astro/calib, gemini.gsfc.nasa.gov/vcs/), about 4000 sources with median positional errors below 1 milliarcsecond (mas) are available. This densification of the VLBA calibrator catalog is a major activity today and will continue into the future. Quasars are strong emitters of radio energy and have the advantage of displaying nearly point-like images. They therefore are potential contributors to the reference system once their positions are accurately determined. The Large Quasar Astrometric Catalog (ftp://syrte.obspm.fr/pub/LQAC) contains over 100 000 quasars with the best available astrometric data, cross-correlating radio and optical information (Andrei *et al.* 2009).

The accuracy of VLBI radio observations can be improved even further to about 10 microarcseconds (μas) using phase-referencing techniques. Observations of radio stars (Boboltz *et al.* 2007), star-forming regions, and the Galactic center are leading to exciting results that are revolutionizing research on the luminosities of massive young stars and the Galactic distance scale (Reid 2008). Source structure analysis, proper motions, and trigonometric distance programs for specific targets are great opportunities for those interested in radio astrometry. Additional information and proposals to observe can be directed through the National Radio Astronomy Observatories NRAO (www.nrao.edu), the European VLBI Network (www.evlbi.org), or the Japanese VLBI Exploration of Radio Astrometry, VERA project (veraserver.mtk.nao.ac.jp/outline/index-e.html).

3.2 Optical astrometry

3.2.1 Differential astrometry

The atmosphere of the Earth acts like a corrugated wave front that distorts the image shape and displaces a star from its true position (see Chapter 9 for a detailed discussion of this topic). Fortunately, this image degradation acts nearly like a Gaussian broadening function, which makes it easier for us to model the shape of the stellar images that we observe. Due to the corrugated wave front, two stars that appear to be very close to each other have their positions displaced by nearly the same amount and therefore their relative positions are essentially unchanged. As a consequence, the accuracy of relative positions is much better

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than that of the individual, absolute positions. The error contribution to astrometric accuracy imposed by the atmosphere is to good approximation proportional to exposure time$^{-1/2}$ and separation$^{1/3}$ (Han 1989; see also Chapter 9). For example, 30 seconds of exposure on two stars separated by 10 arcminutes will yield an accuracy of about 7 mas in their separation, while if the two stars were separated by only 2 arcseconds the accuracy of their separation might be as small as 1 mas. Also, an increase of the integration time by a factor of four will cut the errors in half. This example offers a partial solution to our problem. If one of the pair of stars can be used as a guide star and we can guide sufficiently rapidly to track the atmospheric motions, then the second star and those surrounding it will have their relative positional shifts reduced. This approach is usually called "first-order adaptive optic," or "tip-tilt correction." Full adaptive optics (see Chapters 10 and 11) involves being able to map the shape of the corrugations in real time and distorting a flexible transfer mirror to compensate for the atmospheric corrugations; however, it is a very costly approach. At a good observing site the correlation between the atmospheric shifts is reduced to about 50% for two stars separated by 4 arcminutes, i.e. only half of the time will the two stars be shifted in the same direction. This limitation in the field size for the tip-tilt method means that in order to achieve larger fields of view we must use multiple guide stars, which is an approach developed by Tonry *et al.* (1997) and implemented on the orthogonal-transfer (OT) charge-coupled devices (CCDs) (see also Chapter 14). Large-scale implementation of OT CCDs into arrays have yielded orthogonal-transfer arrays, or OTAs (Tonry *et al.* 2004) that are being used with the Pan-STARRS telescopes (Kaiser *et al.* 2002) and the WIYN one-degree imager (ODI) as described by Jacoby *et al.* (2002). This new technology is revitalizing ground-based astrometry, especially since its use on medium-aperture telescopes yields much fainter limiting magnitudes than will be achievable from space, due to the limited aperture sizes that can now be built and launched. The earlier Mosaic cameras (8k by 8k pixels from eight CCD chips) have been the "workhorse" for many visiting astronomers at the KPNO and CTIO 4-meter telescopes. An astrometric evaluation is presented by Platais *et al.* 2002, 2003, as well as Chapter 19. These instruments were also used for the Deep Astrometric Standards project (Platais *et al.* 2006).

3.2.2 Wide-field astrometry

The concept of differential astrometry can also be applied to wide-field observing with the goal of obtaining extensive catalogs of positions, magnitudes, colors, and proper motions. Traditionally, this has been done with astrographs. Early epoch surveys are still important for astrometry due to the large "leverage" arm for determining accurate proper motions in combination with more recent observations. (A discussion and tables of old and new star catalogs may be found in Chapter 20.) The first all-sky astrometric survey at optical wavelengths with an electronic detector was published as the US Naval Observatory CCD Astrograph Catalog (Zacharias *et al.* 2004). Overlapping fields make it possible to establish a rigid celestial reference frame using block adjustment procedures (Zacharias 1992). Recent progress in detector technology has enabled the production of large single-chip CCDs rivaling the size of photographic plates (Zacharias 2008). Astrometric errors induced by the atmosphere are smaller for longer wavelengths (see Chapter 9). The 2-micron all-sky

survey capitalized on this fact to obtain positions of over 400 million stars accurate to about 80 mas with short integration times, a small field of view, and telescope aperture (Zacharias *et al.* 2006).

3.2.3   Photometric surveys for astrometric research

Given the impressive increases in astrometric accuracy made possible by recent technology and its application to the large gigapixel cameras such as the WIYN ODI camera, we now look at some of the science that is possible. The starting points for many of these projects are the surveys, such as 2MASS, DENIS, and the SDSS recently made with relatively small telescopes. (See Chapter 20, Table 20.3, for details on those surveys.) The value of these primarily photometric surveys is that they enable one to search for groups of stars with possible common origin in color–magnitude arrays and then to determine their proper motions to ascertain if the stars are in fact moving with common proper motions, or determine the mean motion of the stars if we already have reason to believe that they are physically associated.

3.2.4   Studies in Galactic structure (see also Chapter 22)

Key for our understanding of our solar neighborhood, Galactic structure, luminosity function, and evolution of stars are the stellar distances. Unbiased, direct determination of distances can only be provided by trigonometric parallaxes. A century of observations with large refractors led to detailed color–absolute-luminosity (Hertzsprung–Russell) diagrams. The culmination of this effort is the 4th Yale General Catalog of trigonometric parallaxes (van Altena *et al.* 1995).

The Sagittarius dwarf galaxy is merging with the Galaxy as shown by radial velocity measurements. Photometric studies identified potential members of the Sagittarius dwarf and the radial velocities of those stars were determined leading to a number of possible orbit solutions. The determination of the proper motions of those stars (Dinescu *et al.* 2005) leads to a measurement of the tangential velocity of the Sagittarius dwarf and a definitive orbit. Several other possible merging dwarf galaxies are known and a determination of their proper motions would help us to understand the dynamics of their orbital evolution.

Currently accepted Lambda cold-dark-matter (CDM) cosmological models (see also Chapter 28) predict several hundred merging dwarf galaxies within 1 kpc of the Sun (Helmi and White 1999). Unfortunately, only a handful of possible candidates have been identified, which casts doubt on the validity of the model. An alternative possibility is that we have not been able to discover those faint objects. Johnston *et al.* (2002) predict that the velocity dispersion will be 5 km/s or less for the remnants of merging dwarfs. An intensive survey of about 100 square degrees should reveal the presence of about 20–30 streams within about 2 kpc, if they exist. If that number of streams is not identified, then something is clearly amiss with the Lambda CDM model.

The amount of "dark matter" in the local disk is still in dispute and we do not have a reasonably complete count of all stars in our solar neighborhood, a task the RECON project (Henry *et al.* 2006) is tackling. It is now possible to determine parallaxes to an accuracy

of about 0.5 mas for stars as faint as magnitude 21 (see Chapter 21). This faint limiting magnitude will enable us to observe the faintest stars and obtain a complete inventory of the stellar density to an accuracy of 2%. We should then have a complete census of the local mass, which can then be compared to the dynamical mass to yield the amount of dark matter.

3.2.5 Using star clusters as laboratories for stellar evolution (see also Chapter 25)

Star clusters provide us with laboratories to study the formation and evolution of stars, since we have good reason to believe that the stars in a cluster formed from the same cloud of gas and all have approximately the same metal content and age. The only major variable left is the stellar mass, which gives us the perfect opportunity to study the luminosity and temperature changes as a function of mass for a given age and metalicity. Unfortunately, we observe the stars in a cluster against foreground and background contaminating stars. By measuring the relative proper motions of the stars in the field of the cluster we can identify stars not moving with the motion of the cluster. In the past it was necessary to wait 20 to 30 years after the first-epoch plates were taken to repeat them and determine the proper motions. With the new technology we can repeat the exposures after only 2 years. However, the short time needed to complete the study is not the only advantage. One of the main limitations in the past was that the old plates had a bright limiting magnitude and the interesting faint and low mass stars were beyond the old plate limit. Now we can carry out these studies in a 2-year time span to magnitude 22, or by extending the time span a bit to even fainter magnitudes.

3.2.6 Measuring the masses of black holes and stars

Black holes can be the final state of cataclysmic collapse of massive stars as well as a consequence of dynamical friction in the centers of galaxies where multitudes of stars spiral into a common gravitational center. What are the masses of these black holes? Estimates exist from spectroscopic measurements of the widths of spectral lines in the integrated spectra of the cores of those galaxies that are interpreted as the velocities of stars in dynamical equilibrium with the massive black hole. Astrometric measurements of the orbits of stars around the black hole in the center of the Galaxy have recently become available through the application of adaptive optics in the infrared. Over the course of the past decade Genzel *et al.* (1997) and Ghez *et al.* (2008) have measured the orbital parameters of several massive stars as they orbit the center of the Galaxy. Remarkably, by observing in the infrared they can see through 20 visual magnitudes of obscuration and directly determine the mass of the central object to be about one million solar masses, and with great certainty infer that the massive object is a black hole and not a cluster of neutron stars or some other kind of massive object (see also Chapter 10).

Similarly, the masses of stars can be measured with increasing accuracy in double-star systems. Using the technique of speckle interferometry (Labeyrie 1970, and Chapters 23 and 24), multiple very short exposures are combined in a computer to achieve diffraction-limited resolution and measure the separation and position angles of close binary stars (Hartkopf

et al. 2008, Mason *et al.* 2009). Extension of that technique to simultaneous observations at two wavelengths has now made it possible to reach one-quarter of the diffraction limit of the telescope (Horch *et al.* 2006, 2009, 2011). Optical Michelson interferometer observations (see Chapter 11) from the Georgia State University's Center for High Angular Resolution Astronomy (CHARA) array have an even higher resolution (Ten Brummelaar *et al.* 2010). As a result, we can now determine accurate masses of stars for a comparison with stellar evolutionary models that is limited only by the accuracy of the parallaxes, i.e. we are waiting for the Gaia and similar missions to give us definitive parallaxes that will yield 1% masses (see Chapters 23 and 24).

3.2.7 Solar System astrometry

Astrometry could potentially become the life saver for the human race. Over geological timescales the Earth was hit by large asteroids leading to mass extinctions. The goal to detect and determine the orbits of all hazardous near-Earth objects (NEOs) led to significant funding for the Pan-STARRS and LSST projects (Ivezic *et al.* 2008). Astrometric observations of minor planets, natural satellites of major planets, and trans-Neptunian objects (TNOs) form the foundation for orbit determination and Solar System dynamics which eventually will allow us to understand the inventory, history, evolution, and formation of our Solar System (see Chapter 26).

3.2.8 Teaching of astronomy

In closing this chapter, it is important to note that ground-based telescopes offer the only practical solution for teaching observational astronomy and astrometry and training students in the methods of observation. It is of course possible to utilize observations taken from satellites as teaching materials, but the ability to experiment with different observational methods and to repeat those observations is greatly diminished. For these reasons there is a continuing need for ground-based astrometry even in the era of high-accuracy space astrometry. Last but not least, astrometry is technology driven. Ground-based telescopes provide the means of testing new hardware and software.

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